SAMPLE

The Periodic Table

How the Elements Are Organized

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Introduction

What we perceive as water, fire, plants, or humans are merely combinations of atoms in the void, as the ancient atomists guessed, and the periodic table is humanity's map of every kind of atom that has proved to exist. The periodic table is an arrangement of the chemical elements, structured by their atomic number, electron configuration and recurring chemical properties. In the basic form, elements are presented in order of increasing atomic number, in the reading sequence. Elements in the same group tend to show similar chemical characteristics, and vertical, horizontal and diagonal trends characterize the periodic table from edge to edge.

The history of the periodic table reflects over two centuries of growth in the understanding of the chemical and physical properties of the elements, with major contributions made by Antoine-Laurent de Lavoisier, Johann Wolfgang Döbereiner, John Newlands, Julius Lothar Meyer, Dmitri Mendeleev, Glenn T. Seaborg, and others. It is also a history of the discovery of the chemical elements themselves, and the story of the periodic table is still being written.

The chapters that follow trace that story from its beginnings in ancient speculation to the laboratories that hunt for element 119: how the table came to be discovered and what it means, how it is organized and why, the atomic physics underneath it, how the elements are observed and measured, and the debates that still surround the most familiar chart in science.

Chapter 1: The Discovery of The Periodic Table

In the 5th century BCE, Leucippus and his pupil Democritus proposed that all matter was composed of small indivisible particles which they called "atoms". Around 330 BCE, the Greek philosopher Aristotle proposed that everything is made up of a mixture of one or more roots, an idea originally suggested by the Sicilian philosopher Empedocles. The four roots, which the Athenian philosopher Plato called elements, were earth, water, air and fire. Similar ideas existed in other ancient traditions, such as Indian philosophy with five elements: Earth, water, fire, air and aether collectively called 'pañca bhūta'. In 1661, Boyle defined elements as "those primitive and simple Bodies of which the mixt ones are said to be composed, and into which they are ultimately resolved."

The first person in recorded history to discover a new element was Hennig Brand, a bankrupt German merchant. Brand tried to discover the philosopher's stone—a mythical object that was supposed to turn inexpensive base metals into gold. In 1669, or later, his experiments with distilled human urine resulted in the production of a glowing white substance, which he called "cold fire" (kaltes Feuer). He kept his discovery secret until 1680, when Anglo-Irish chemist Robert Boyle rediscovered phosphorus and published his findings. The discovery of phosphorus helped to raise the question of what it meant for a substance (any given variety of matter) to be an element, in a world where versions of atomic theory were only speculative and later understandings of the nature of substances were only beginning to become possible.

In 1718, Étienne François Geoffroy's Affinity Table made use of several aspects — (1) tabular grouping and (2) correlation with chemical affinity — that would later be reprised. In 1789, French chemist Antoine Lavoisier wrote Traité Élémentaire de Chimie (Elementary Treatise of Chemistry), which is considered to be the first modern textbook about chemistry. Lavoisier defined an element as a substance whose smallest units cannot be broken down into a simpler substance. Lavoisier's book contained a list of "simple substances" that Lavoisier believed could not be broken down further, which included oxygen, nitrogen, hydrogen, phosphorus, mercury, zinc and sulfur. This formed the basis for the modern list of elements.

Lavoisier's list also included "light" and "caloric", which at the time were believed to be material substances. While many leading chemists refused to believe Lavoisier's new revelations, the Elementary Treatise was written well enough to convince the younger generation. However, Lavoisier's descriptions of his elements lack completeness, as he only classified them as metals and non-metals. In 1808-10, British natural philosopher John Dalton published a

method by which to arrive at provisional atomic weights for the elements known in his day, from stoichiometric measurements and reasonable inferences. Dalton's atomic theory was adopted by many chemists during the 1810s and 1820s. In 1815, British physician and chemist William Prout noticed that atomic weights seemed to be multiples of that of hydrogen.

In 1817, German physicist Johann Wolfgang Döbereiner began one of the earliest attempts to classify the elements. In 1829, he found that he could form some of the elements into groups of three, with the members of each group having related properties. Chlorine, bromine, and iodine formed a triad; as did calcium, strontium, and barium; lithium, sodium, and potassium; and sulfur, selenium, and tellurium. Various chemists continued his work and were able to identify more and more relationships between small groups of elements.

However, they could not build one scheme that encompassed them all. In 1843, building on work done by Döbereiner, Leopold Gmelin developed a forerunner of the modern periodic table that listed 55 chemical elements grouped by common characteristics. Even though Amedeo Avogadro and, independently of him, André-Marie Ampère, proposed the solution in the form of diatomic molecules and Avogadro's law already in the 1810s, it was not until after Stanislao Cannizzaro's publications in late 1850s when the theory began to be widely considered. In 1860, the modern scientific consensus emerged at the first international chemical conference, the Karlsruhe Congress, and a revised list of elements and atomic masses was adopted. It helped spur creation of more extensive systems.

The first such system emerged in two years. Properties of the elements, and thus properties of light and heavy bodies formed by them, are in a periodic dependence on their atomic weight. French geologist Alexandre- Émile

Béguyer de Chancourtois noticed that the elements, when ordered by their atomic weights, displayed similar properties at regular intervals. In 1862, he devised a three-dimensional chart, named the "telluric helix", after the element tellurium, which fell near the center of his diagram. With the elements arranged in a spiral on a cylinder by order of increasing atomic weight, de Chancourtois saw that elements with similar properties lined up vertically.

The original paper from Chancourtois in Comptes rendus de l'Académie des Sciences did not include a chart and used geological rather than chemical terms. In 1863, he extended his work by including a chart and adding ions and compounds. John Newlands published a letter in the Chemical News in February 1863 on the periodicity among the chemical elements. The next attempt was made in 1864. This last option has nonetheless been criticized by

the chemist and philosopher of science Eric Scerri on the grounds that it appears to imply that hydrogen is above the periodic law altogether, unlike all the other elements.

The first periodic table to become generally accepted was that of the Russian chemist Dmitri Mendeleev in 1869; he formulated the periodic law as a dependence of chemical properties on atomic mass. In a paper dated December 1869 which appeared early in 1870, Meyer published a new periodic table of 55 elements, in which the series of periods are ended by an element of the alkaline earth metal group. The paper also included a line chart of relative atomic volumes, which illustrated periodic relationships of physical characteristics of the elements, and which assisted Meyer in deciding where elements should appear in his periodic table. By this time he had already seen the publication of Mendeleev's first periodic table, but his work appears to have been largely independent. In 1869, Russian chemist Dmitri Mendeleev arranged 63 elements by increasing atomic weight in several columns, noting recurring chemical properties across them.

Mendeleev used the trends he saw to suggest that atomic weights of some elements were incorrect, and accordingly changed their placements: for instance, he figured there was no place for a trivalent beryllium with the atomic weight of 14 in his work, and he cut both the atomic weight and valency of beryllium by a third, suggesting it was a divalent element with the atomic weight of 9.4. Mendeleev widely distributed printed broadsheets of the table to various chemists in Russia and abroad. Mendeleev argued in 1869 there were seven types of highest oxides. Compared to the rest of the work, Mendeleev's 1869 list misplaces seven then known elements: indium, thorium, and five rare-earth metals: yttrium, cerium, lanthanum, erbium, and didymium. The last two were later found to be mixtures of two different elements; ignoring those would allow him to restore the logic of increasing atomic weight.

These elements (all thought to be divalent at the time) puzzled Mendeleev as they did not show a regular increase in valency despite their seemingly consequential atomic weights. He measured the heat capacity of indium, uranium, and cerium to demonstrate their higher assumed valency, which was soon confirmed by Prussian chemist Robert Bunsen. Mendeleev grouped them together, thinking of them as of a particular kind of series. Within 100 years of the appearance of Mendeleev's table in 1869, Edward G. Mazurs had collected an estimated 700 different published versions of the periodic table. Many forms retain the rectangular structure, including Charles Janet's left-step periodic table (pictured below), and the modernised form of Mendeleev's original 8-column layout that is still common in Russia. Mendeleev continued

to improve his ordering; in 1870, it gained a tabular shape, and each column was given its own highest oxide, and in 1871, he further developed it and formulated what he termed the "law of periodicity".

Some changes also occurred with new revisions, with some elements changing positions. In 1870, he first tried to characterize the yet undiscovered elements, and he gave detailed predictions for three elements, which he termed eka-boron, eka-aluminium, and eka-silicium; he also more briefly noted a few other expectations. In early 1870, he decided that the weights for these elements must be wrong and that the rare-earth metals should be trivalent (which accordingly increased their predicted atomic weights by half). In 1871, Mendeleev expanded his predictions further. Having had no success in that, he abandoned his attempts to incorporate the rare-earth metals in late 1871 and embarked on his grand idea of luminiferous ether.

His idea was carried on by Austrian-Hungarian chemist Bohuslav Brauner, who sought to find a place in the periodic table for the rare-earth metals; Mendeleev later referred to him as to "one of the true consolidators of the periodic law". In addition to the predictions of scandium, gallium, and germanium that were quickly realized, Mendeleev's 1871 table left many more spaces for undiscovered elements, though he did not provide detailed predictions of their properties. In total, he predicted eighteen elements, though only half corresponded to elements that were later discovered. In the years following Mendeleev's publication, the Indian chemist Prafulla Chandra Ray began working with English geologist Thomas Henry Holland to search for "certain rare Indian minerals in the expectation that one or two new elements might turn up and thus fill up the gap in Mendeleev's periodic table." None of the proposals were accepted immediately, and many contemporary chemists found it too abstract to have any meaningful value.

Of those chemists that proposed their categorizations, Mendeleev strove to back his work and promote his vision of periodicity, Meyer did not promote his work very actively, and Newlands did not make a single attempt to gain recognition abroad. Both Mendeleev and Meyer created their respective tables for their pedagogical needs; the difference between their tables is well explained by the fact that the two chemists sought to use a formalized system to solve different problems. Mendeleev's intent was to aid composition of his textbook, Foundations of Chemistry, whereas Meyer was rather concerned with presentation of theories.

Mendeleev's predictions emerged outside of the pedagogical scope in the realm of journal science, while Meyer made no predictions at all and explicitly stated his table and his textbook it was contained in, Modern Theories, should

not be used for prediction in order to make the point to his students to not make too many purely theoretically constructed projections. Mendeleev and Meyer differed in temperament, at least when it came to promotion of their respective works.

Boldness of Mendeleev's predictions was noted by some contemporary chemists, however skeptical they may have been. Meyer referred to Mendeleev's "boldness" in an edition of Modern Theories, whereas Mendeleev mocked Meyer's indecisiveness to predict in an edition of Foundations of Chemistry. Eventually, the periodic table was appreciated for its descriptive power and for finally systematizing the relationship between the elements, although such appreciation was not universal. Mendeleev's eka-aluminium was discovered in 1875 and became known as gallium; eka-boron and eka-silicium were discovered in 1879 and 1886, respectively, and were named scandium and germanium. Mendeleev was even able to correct some initial measurements with his predictions, including the first prediction of gallium, which matched eka-aluminium fairly closely but had a different density.

Mendeleev advised the discoverer, French chemist Paul-Émile Lecoq de Boisbaudran, to measure the density again; de Boisbaudran was initially skeptical (not least because he thought Mendeleev was trying to take credit from him) but eventually admitted the correctness of the prediction. Mendeleev contacted all three discoverers; all three noted the close similarity of their discovered elements with Mendeleev's predictions, with the last of them, German chemist Clemens Winkler, admitting this suggestion was not first made by Mendeleev or himself after the correspondence with him, but by a different person, German chemist Hieronymous Theodor Richter. Some contemporary chemists were not convinced by these discoveries, noting the dissimilarities between the new elements and the predictions or claiming those similarities that did exist were coincidental. However, success of Mendeleev's predictions helped spread the word about his periodic table. Later, chemists used the successes of these Mendeleev's predictions to justify his table.

In 1881, Mendeleev claimed priority over Meyer for the periodic table as follows: That person is rightly regarded as the creator of a particular scientific idea who perceives not merely its philosophical, but its real aspect, and who understands so to illustrate the matter so that everyone can become convinced of its truth. Then alone the idea, like matter, becomes indestructible. Even as Mendeleev corrected positions of some elements, he thought that some relationships that he could find in his grand scheme of periodicity could not be found because some elements were still undiscovered, and that the properties of such undiscovered elements could be deduced from their expected relationships with other elements.

In 1881, Mendeleev and Meyer had an argument via an exchange of articles in British journal Chemical News over priority of the periodic table, which included an article from Mendeleev, one from Meyer, one of critique of the notion of periodicity, and many more. In 1882, the Royal Society in London awarded the Davy Medal to both Mendeleev and Meyer for their work to classify the elements; although two of Mendeleev's predicted elements had been discovered by then, Mendeleev's predictions were not at all mentioned in the prize rationale.

Eka-silicon was found in 1886 by German chemist Clemens Winkler, who named it germanium. The properties of gallium, scandium, and germanium matched what Mendeleev had predicted. Mendeleev believed it to be a very light gas, with an atomic weight several orders of magnitude smaller than that of hydrogen. He also postulated that it would rarely interact with other elements, similar to the noble gases of his group zero, and instead permeate substances at a velocity of 2,250 kilometers (1,400 mi) per second. Mendeleev was not satisfied with the lack of understanding of the nature of this periodicity; this would only be possible through the understanding of the composition of the atom.

In 1889, Mendeleev noted at the Faraday Lecture to the Royal Institution in London that he had not expected to live long enough "to mention their discovery to the Chemical Society of Great Britain as a confirmation of the exactitude and generality of the periodic law". In the same lecture he allowed that "we already feel that we have neared the moment when this [periodic] law begins to change, and change fast". Even the discovery of the noble gases at the close of the 19th century, which Mendeleev had not predicted, fitted neatly into his scheme as an eighth main group.

Mendeleev nevertheless had some trouble fitting the known lanthanides into his scheme, as they did not exhibit the periodic change in valencies that the other elements did. By 1890, Mendeleev's periodic table had been universally recognized as a piece of basic chemical knowledge. Apart from his own correct predictions, a number of aspects may have contributed to this, such as the correct accommodation of many elements whose atomic weights were thought to have wrong values but were later corrected.

The debate on the position of the rare-earth metals helped spur the discussion about the table as well. The great value of Newland's, Mendeleef's, and Lothar Meyer's generalisation, known as the periodic arrangement of the elements, is universally acknowledged. Although Mendeleev knew of lanthanum, cerium, and erbium, they were previously unaccounted for in the table because their total number and exact order were not known; Mendeleev still could not fit

them in his table by 1901. This was in part a consequence of their similar chemistry and the imprecise determination of their atomic masses. Mendeleev himself added these elements to the table as group 0 in 1902, without disturbing the basic concept of the periodic table.

However, Mendeleev firmly believed that future would only develop the notion rather than challenge it and reaffirmed his belief in writing in 1902. After much investigation, the Czech chemist Bohuslav Brauner suggested in 1902 that the lanthanides could all be placed together in one group on the periodic table. Mendeleev treated the change by assessing each element to an individual place in his system of the elements rather than continuing to treat them as a series. Mendeleev noticed that there was a significant difference in atomic mass between cerium and tantalum with no element between them; his consideration was that between them, there was a row of yet undiscovered elements, which would display similar properties to those elements which were to be found above and below them: for instance, an eka-molybdenum would behave as a heavier homolog of molybdenum and a lighter homolog of wolfram (the name under which Mendeleev knew tungsten). However, the higher valency for didymium had not been established, and Mendeleev tried to do so himself.

By 1904, Mendeleev's table rearranged several elements, and included the noble gases along with most other newly discovered elements. He determined that the rare-earth elements (lanthanides), 13 of which were known, lay within that gap. The contemporarily accepted discovery of element 75 came in 1925, when Walter Noddack, Ida Tacke, and Otto Berg independently rediscovered it and gave it its present name, rhenium.) British chemist John Newlands presented in Chemical News a classification of the 62 known elements. Newlands noticed recurring trends in physical properties of the elements at recurring intervals of multiples of eight in order of mass number; based on this observation, he produced a classification of these elements into eight groups.

Each group displayed a similar progression; Newlands likened these progressions to the progression of notes within a musical scale. Newlands's table left no gaps for possible future elements, and in some cases had two elements at the same position in the same octave. Newlands's table was ignored or ridiculed by some of his contemporaries. The Chemical Society refused to publish his work. The president of the society, William Odling, defended the society's decision by saying that such "theoretical" topics might be controversial; there was even harsher opposition from within the society, suggesting the elements could have been just as well listed alphabetically.

Later that year, Odling suggested a table of his own but failed to get

recognition following his role in opposing Newlands's table. German chemist Lothar Meyer also noted the sequences of similar chemical and physical properties repeated at periodic intervals. But a study of this arrangement, it must be allowed, is a somewhat tantalising pleasure; for, although the properties of elements do undoubtedly vary qualitatively, and, indeed, show approximate quantitative relations to their position in the periodic table, yet there are inexplicable deviations from regularity, which hold forth hopes of the discovery of a still more far-reaching generalisation. What that generalisation may be is not yet to be divined; but that it must underlie what is known, and must furnish a clue to the explanation of irregularities, cannot be disputed.

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Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

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She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.